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Which surface atmospheric variable drives the seasonal cycle of sea surface temperature over the global ocean?

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[1] The impact of near-surface atmospheric variables used in driving the seasonal cycle of climatological mean sea surface temperature (SST) is quantified over the global ocean. The six atmospheric variables are air temperature, vapor mixing ratio, wind speed, precipitation, net shortwave radiation, and net longwave radiation, the first (last) three just above (at) the sea surface. Atmospherically forced ocean general circulation model (OGCM) simulations with no data assimilation are performed using monthly and annual means of those variables under the assumption that variations in climatological monthly SSTs are driven by atmospheric variables. SSTs resulting from these simulations are compared with those from a satellite-based field to determine the impact of each atmospheric variable. Large spatial variability is found in the order of impact (most to least) of six atmospheric variables. In general, the SST seasonal cycle is driven primarily by shortwave radiation at midlatitudes, but wind speed is the major controlling variable in the Indian Ocean. Precipitation has almost no significant influence on monthly SST. Overall, shortwave radiation is the most influential variable controlling the seasonal cycle of SST over 34.3% of the global ocean. Wind speed is the second most important variable (27.2%). In tropical regions and the Arabian Sea, sources other than the atmospheric thermal forcing are found to play a significant role in regulating the SST seasonal cycle.

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1. Introduction

[2] Sea surface temperature (SST) is a key component of the ocean-atmosphere system, since it has great influence on regulation of the climate system [e.g., McPhaden, 1999; Elsner and Kara, 1999]. Climatological SST exhibits notable spatial and temporal variability over the global ocean (Figure 1). For example, as evident from these fields obtained from National Oceanic and Atmospheric Administration (NOAA) climatology [Reynolds *et al.*, 2002], there are clearly strong seasonal variations, especially from mid-latitudes to high latitudes. These variations are seen in both hemispheres in February and August in comparison to the long-term climatological mean SST.

[3] It is well known that SST is the ocean variable that most strongly impacts the atmosphere. However, atmospheric forcing variables have an impact on ocean model SST, and the effects of these variables are not well known. Investigating the relative impacts of atmospheric forcing variables on the seasonal cycle of SST and the spatial

variation of that impact over the global ocean is the focus of this study.

[4] Earlier regional studies indicated that the net heat flux is the main contributor to SST variability [Frankignoul, 1985; Cayan, 1992]. Evaporation directly affects SST on short (e.g., diurnal) time scales but can also change the salinity of seawater, thereby affecting SST on longer (e.g., monthly) time scales [e.g., Perigaud *et al.*, 2003]. To complement these studies, we quantify the role of various atmospheric variables in driving the seasonal cycle of SST regionally, something that has not been established over the global ocean. In addition to the atmospheric factors, the seasonal cycle of SST is also influenced by the ocean circulation through oceanic advection [e.g., Hogg *et al.*, 2006]. Our assumption here is that such dynamical processes are mainly caused by the direct effects of atmospheric variables near or at the sea surface (such as winds and net solar radiation).

[5] In this paper, we present a quantitative analysis to investigate the order of impact (most to least) of atmospheric variables that drive the SST seasonal cycle. Atmospherically forced simulations with no assimilation of SST data, performed with an ocean general circulation model (OGCM) that accounts for mixed layer physics, are used for this purpose. Such an ocean model is essential since at present observations are not adequate to carry out such extensive diagnostic studies over the global ocean. Our main goal is not only to find which atmospheric variable mainly

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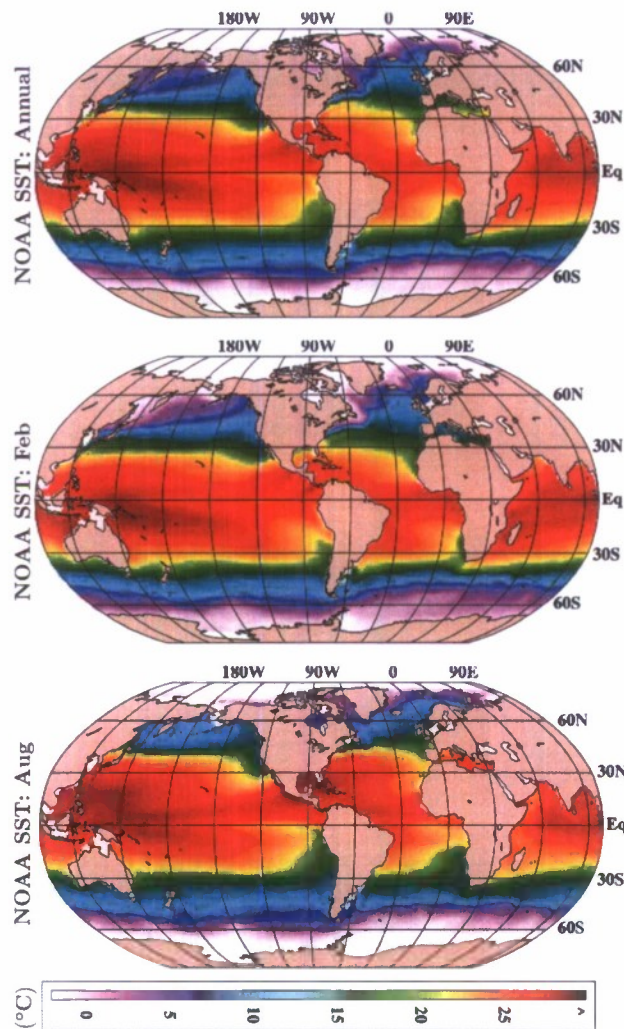


Figure 1. Climatological (annual) mean SST along with climatological monthly mean SST in February and August. They are obtained from the NOAA climatology based on the time period 1971–2000 [Reynolds *et al.*, 2002].

regulates the SST seasonal cycle, but also to determine where in the global ocean that variable is most important. Results are presented through comprehensive statistical analyses.

2. Ocean Model

[6] The Hybrid Coordinate Ocean Model (HYCOM) introduced by Bleck [2002] is used in this study. It is a primitive equation model with advantages of isopycnal, terrain-following (σ) and pressure (approximately z level) coordinates in optimally simulating coastal and open-ocean circulation features [Chassignet *et al.*, 2006]. Only a brief description of the model is provided here (see Appendix A for some details).

[7] HYCOM is configured for the global ocean, spanning from 78°S to 90°N. It has $0.72^\circ \times 0.72^\circ \cos(\text{lat})$ (longitude \times latitude) resolution on a Mercator grid south of 47°N. The

model has a bipolar cap to avoid a singularity north of 47°N. Average zonal (longitudinal) grid resolution varies from ≈ 80 km at the equator to ≈ 60 km at midlatitudes (e.g., at 40°N). The meridional (latitudinal) grid resolution is doubled near the equator to better resolve the equatorial waveguide and halved in the Antarctic for computational efficiency. Hereinafter, the model resolution will be referred to as 0.72° for simplicity.

[8] There is no assimilation of any ocean data, including SST, and no relaxation to any other data except for a relaxation to a monthly mean sea surface salinity climatology from the Polar Science Center (PSC) Hydrographic Climatology (PHC) to keep the evaporation-precipitation balance on track in the model. The PHC climatology is chosen for its accuracy in the Arctic region [Steele *et al.*, 2001]. Lack of data assimilation in the model simulations allows us to use them in examining the impacts of different atmospheric forcing variables on SST over the global ocean, the major focus of this investigation.

2.1. Atmospheric Forcing

[9] The model reads in the following time-varying atmospheric fields: for the momentum equation forcing (zonal and meridional components of wind stress) and for the thermal forcing (air temperature, air mixing ratio, and wind speed at 10 m above the sea surface; precipitation, net shortwave radiation, and net longwave radiation at the sea surface). These are given in Table 1, along with their notation used in the figures (e.g., Figure 2) and throughout the text.

[10] Climatological monthly means of atmospheric forcing variables (i.e., 12 monthly sets of fields) were formed from the $1.125^\circ \times 1.125^\circ$ European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalysis during 1979–2002 [Uppala *et al.*, 2005]. However, a high-frequency component (linearly interpolated to every 6 hours) is added to the climatological forcing because the mixed layer is sensitive to variations in surface atmospheric forcing on

Table 1. Atmospheric Forcing Variables Used for Thermal Forcing in the OGCM Simulations^a

| Variable | Description of the Atmospheric Variable Used Throughout the Text |
|--------------|--|
| airtemp | air temperature at 10 m above the sea surface ($^\circ\text{C}$) |
| precip | precipitation over the sea surface (m s^{-1}) |
| vapormix | mixing ratio of air at 10 m above the sea surface (g kg^{-1}) |
| shortwave | net shortwave radiation at the sea surface (W m^{-2}) |
| longwave | net longwave radiation at the sea surface (W m^{-2}) |
| windspd | wind speed at 10 m above the sea surface (m s^{-1}) |
| Simulation | Atmospheric Forcing Used for the Ocean Model Simulation |
| 1. monthly | monthly mean atmospheric forcing for each variable |
| 2. airtemp | the same as simulation 1 but for annual mean airtemp |
| 3. precip | the same as simulation 1 but for annual mean precip |
| 4. vapormix | the same as simulation 1 but for annual mean vapormix |
| 5. shortwave | the same as simulation 1 but for annual mean shortwave |
| 6. longwave | the same as simulation 1 but for annual mean longwave |
| 7. windspd | the same as simulation 1 but for annual mean windspd |
| 8. annual | annual mean atmospheric forcing for each variable |

^a Atmospheric variables used for forcing the model are provided along with their abbreviations. Eight model simulations forced by these variables are given. Simulation 1 (8) was performed using the monthly (annual) mean of each variable at each HYCOM grid over the global ocean.

time scales of a day or less [e.g., *Wallcraft et al.*, 2003; *Kara and Hurlburt*, 2006]. These hybrid winds consist of monthly winds from ERA-40 plus ECMWF intramonthly wind anomalies. The 6-hr anomalies are obtained from a reference year. For this purpose, the winds from September 1994 through September 1995 (6 hr) are used because they represented a typical annual cycle of the ECMWF 10 m winds, and because the September winds in 1994 and 1995 most closely matched each other. The 6-hr September 1994 and September 1995 wind stresses are blended to make a complete annual cycle. Further details are provided by *Wallcraft et al.* [2003].

[11] Given the deficiencies existing in the original ERA-40 fields, a climatological mean correction is applied to some fields obtained from ERA-40. The accuracy of the ERA-40 winds is further improved by correcting them based on the satellite winds (QuikSCAT) using a linear regression analysis, as further described by *Kara et al.* [2009]. That study also reveals that regression-corrected winds significantly improve the accuracy of the SSTs from the model. The correction is necessitated by the fact that one cannot use the twice-daily QuikSCAT winds directly in an OGCM simulation since there can be data voids, depending on the coverage of the satellite passes. However, a correction based on the QuikSCAT monthly mean wind speeds can improve the accuracy of the 3-hourly ERA-40 winds, which can then be used for forcing an OGCM. A correction for shortwave and longwave fluxes from ERA-40 is made using data from the International Satellite Cloud Climatology Project (ISCCP) described by *Rossow and Zhang* [1995]. Precipitation at the sea surface used in HYCOM simulations is obtained from ERA-40 but corrected with data from the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003].

[12] Climatological mean forcing fields are shown in Figure 8 for February and August. Also given are the long-term climatological means for each variable as formed from the 12-monthly climatological means. Clearly, there are seasonal variations for each variable over the global ocean, and we will investigate the impact of such seasonal changes on the SST seasonal cycle.

2.2. Model Simulations

[13] All the HYCOM simulations (Table 1) are performed with the 0.72° resolution model configured for the global ocean. In this study, the 0.72° resolution HYCOM, rather than its finer resolution counterparts, is preferred for computational efficiency, allowing us to perform many simulations in a short time. A 1-year simulation takes ≈ 11 wall-clock hours using 64 HP/COMPACT SC45 processors.

[14] A resolution of 0.72° is generally sufficient for studying monthly SST, except in western boundary currents (e.g., Kuroshio and Gulf Stream), where advection and mesoscale eddies are important. Each simulation was spun-up for about 5 years until statistical equilibrium was reached, and then extended another 4 more years. A linear regression analysis was performed for domain averaged quantities (layer temperature, salinity, potential and kinetic energy, etc.) to investigate statistical equilibrium in each layer. The model is deemed to be in statistical equilibrium when the rate of potential energy change is acceptably small (e.g., $<1\%$ in 5 years) in all layers. For the analysis, monthly

mean HYCOM SST climatologies are constructed from SSTs obtained from model years 5 through 9.

[15] The model run denoted as “monthly” is the standard simulation which uses monthly mean atmospheric forcing for each variable (Figure 2). All other simulations are identical to the standard simulation except that the climatological annual mean replaces the monthly mean of one atmospheric variable. For example, simulation 2 in Table 1 (denoted as *airtemp*) uses climatological mean air temperature at each model grid point over the global ocean with monthly means for all other forcing parameters. Similarly, simulation 3 (*precip*) uses annual mean precipitation with monthly means for all other forcing parameters. Simulation 8 uses annual mean atmospheric forcing for each variable. Here, we need to emphasize that annual mean represents the average of climatological monthly mean values, i.e., it is not the average calculated over 12 months for a specific year. Hereinafter, for simplicity, the term “annual” will be used in place of the climatological mean.

[16] One might ask why we use the annual mean of one atmospheric forcing variable (versus climatological monthly means for the others) to determine importance of the annual mean variable in driving the SST seasonal cycle? Obviously, one could argue that an atmospheric variable may be completely ignored (i.e., by using a zero field) to investigate the importance of that variable. However, such an approach is not appropriate, given that the atmospheric forcing fields do exist in the actual climate system. In addition, we represent the actual variations of SST in the climate system by using an ocean model that is forced with air-sea fluxes obtained via efficient and realistic bulk parameterizations (see Appendix A). By using annual means for atmospheric forcing variables, realistic bounds for the heat fluxes are maintained.

[17] The focus of this study is the impact of individual atmospheric thermal forcing variables on the seasonal variations of SST. We do not perform simulations that use the annual mean wind stress field. We leave wind stress alone precisely because it dominates ocean dynamics and it is not our intent to study changes in dynamics (e.g., in ocean currents). When we use annual mean wind speed, there is some inconsistency in separating wind speed and wind stress, but the same is true to some extent when we hold any single atmospheric field at its annual mean.

[18] Similarly, we do not replace the monthly means of sensible and latent fluxes by their annual means to examine the impact of heat fluxes on SST. The reason is that driving HYCOM directly by sensible and latent heat flux is not practical in the context of a bulk parameterization that uses the model SST. As mentioned in Appendix A, exchange coefficients for sensible and latent heat fluxes include air temperature (atmospheric forcing) and model SST. Instead, we use the six variables that are included in the thermal forcing for the ocean models, namely near-surface air temperature, precipitation, near-surface air mixing ratio, shortwave radiation, longwave radiation and near-surface wind speed. This approach should help direct ocean modelers, coupled atmosphere-ocean modelers and researchers performing air-sea interaction studies to focus on the accuracy of the atmospheric forcing variables with the greatest impact on a global and regional basis. It should

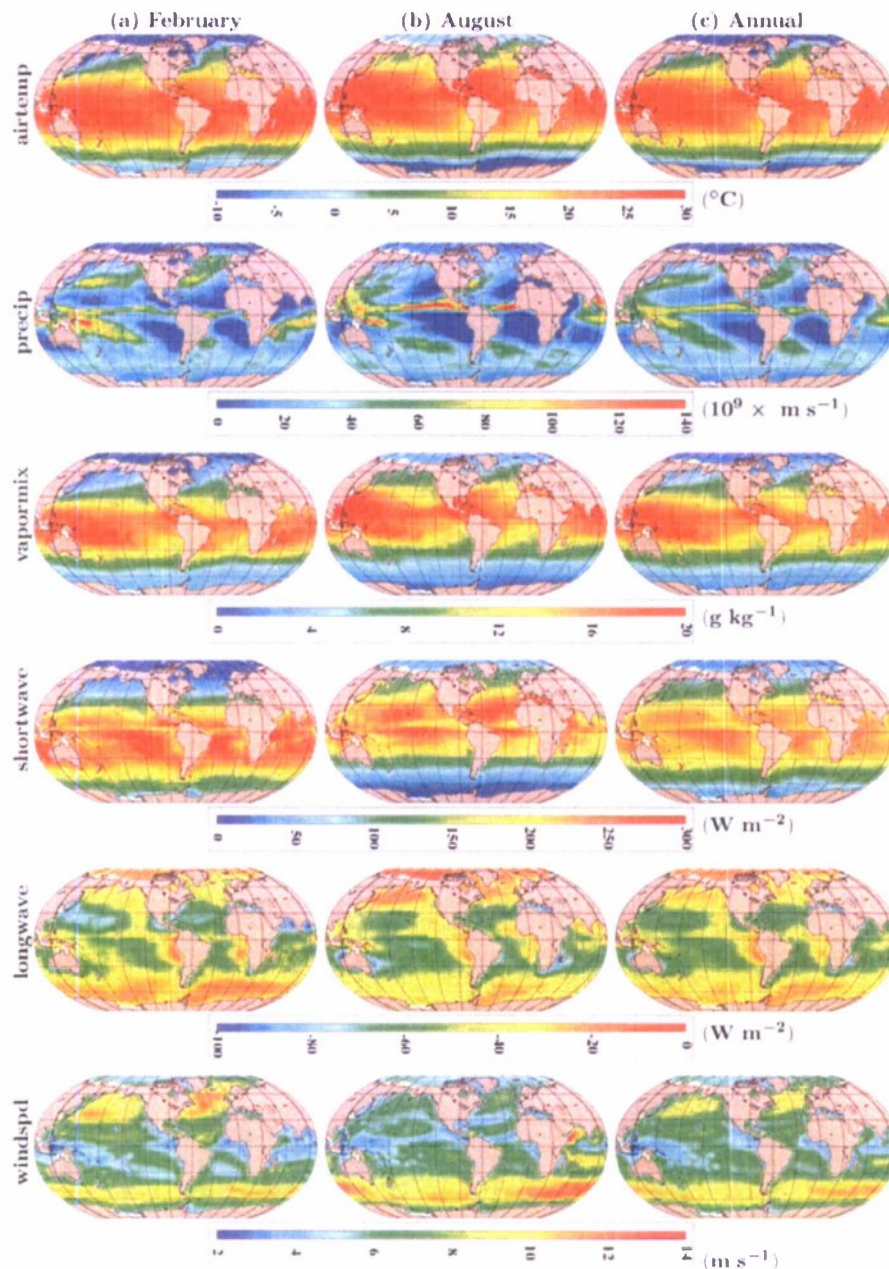


Figure 2. Monthly mean climatologies of atmospheric variables in February and August along with their climatological means as obtained from ERA-40 during 1979–2002. Corrections were applied to the original solar radiation, precipitation, and wind speed fields (see section 2.1).

also assist in interpretation and improvements of model results.

3. Methodology for SST Analyses

[19] Given that all forcing in the HYCOM simulations is climatological, monthly mean HYCOM SSTs can be compared with observed climatological monthly mean SSTs. These comparisons are designed to examine the accuracy of the SST generated by the given atmospheric forcing set (Table 1). For evaluation, monthly mean HYCOM SSTs

are formed from daily model output. The NOAA SST climatology [Reynolds *et al.*, 2002] is taken as a reference (truth). Its resolution ($1^\circ \times 1^\circ$) is close to that of HYCOM ($0.72^\circ \times 0.72^\circ \cos(\text{lat})$).

[20] Different statistical measures are considered together in order to measure the strength of the relationships between SST values simulated by the model (HYCOM) and those obtained from the climatology (NOAA). The latter is interpolated to the model grid for model-data comparisons. We evaluate time series of monthly mean SST at each model

grid point over the global ocean. Following *Murphy* [1988], the statistical relationships used in comparisons between monthly mean NOAA SST (X) and HYCOM SST (Y) can be expressed as follows:

$$\text{Bias} = \bar{Y} - \bar{X}, \quad (1)$$

$$\text{RMS} = \left[\frac{1}{n} \sum_{i=1}^n (Y_i - X_i)^2 \right]^{1/2}, \quad (2)$$

$$\text{Skill} = 1 - (\text{RMS}^2 / \sigma_X^2), \quad (3)$$

where $n = 12$ because we evaluate monthly mean SSTs from January through December.

[21] The bias given in (1) is the annual mean error, and RMS is the root-mean-square difference over the seasonal cycle. Skill score based on RMS is nondimensional. \bar{X} (\bar{Y}) and σ_X (σ_Y) are the means and standard deviations of the NOAA (HYCOM) SST values over the annual cycle at each ocean grid point of the global ocean. The annual means are not removed from the time series before calculating RMS because we are not interested in determining whether the two variables are uncorrelated after the seasonal effects are removed.

[22] The skill score in (3), hereinafter referred to skill only, is a particularly significant evaluation metric for SST. The reason is that biases are taken into account in the RMS difference, but the latter can be small where skill is low because the amplitude of the seasonal cycle is small in some regions (e.g., the equatorial Pacific warm pool). The skill is 1.0 for perfect HYCOM SSTs in comparison to the reference NOAA SSTs. Positive skill is usually considered to represent a minimal level of acceptable performance [Murphy, 1995].

4. SST Accuracy Versus Atmospheric Forcing

[23] In Figure 3 we compare monthly mean SSTs from each HYCOM simulation (Table 1) to those from the NOAA climatology using the statistical metrics described above. Results are shown only for ice-free regions because the focus of this paper is the importance of atmospheric forcing on SST rather than sea-ice. The ice-free regions over the global ocean are determined using an ice-land mask based on the study of *Reynolds et al.* [2002]. Ice-covered regions are shown in gray on all maps.

[24] The standard simulation (i.e., monthly means for all the atmospheric variables) provides a very accurate representation of climatological mean SST, and it is the one that best simulates SST over the global ocean (Figure 3). We examine the accuracy of monthly SSTs obtained from the standard HYCOM simulation as well as others using each of the statistical metrics. This is necessary because each metric provides different information about the model performance in comparison to the observational data.

[25] A striking feature evident from the statistical error maps (Figure 3) is that there are no significant differences in annual mean SST bias among the simulations, except for those forced with the annual mean of each atmospheric variable and annual mean wind speed (Figure 3a). The

global average of model SST bias with respect to the NOAA SSTs is negligible (\approx zero) in all simulations (Table 2). The similarity of the biases in most of the simulations is confirmed from the zonal averages of bias values over the global ocean (Figure 4). Even for the HYCOM simulation forced with the annual mean of each atmospheric forcing variable, the globally averaged annual mean SST bias has a very small value of -0.12°C .

[26] Obviously, small differences in the bias fields do not really imply that all simulations perform similarly. This result only demonstrates that the annual mean SST bias does not change significantly over the global ocean when using the annual mean of any of the atmospheric variables. It is encouraging that a mean atmosphere generates a realistic mean SST, even though the simulation forced with the annual mean of all atmospheric variables produces a constant SST with almost no seasonal variation at a given grid point. This validates our approach of using annual mean fields in forcing the model.

[27] Unlike the mean SST bias over the global ocean, RMS differences with respect to NOAA SSTs calculated over the seasonal cycle at each ocean model grid (Figure 3b) are not generally similar for all simulations (Table 1). As expected, the HYCOM simulation using the annual mean of all atmospheric forcing parameters results in the least accurate SST in comparison to the NOAA SSTs. The simulation using annual mean shortwave radiation with monthly means of remaining forcing parameters otherwise yields the highest RMS SST difference globally (Table 2). In this case, the global average of RMS SST difference (0.84°C) increases $\approx 27\%$ in comparison to the standard all monthly simulation (0.66°C). Hence shortwave radiation is the most important single parameter in controlling the SST seasonal cycle over the global ocean. The use of annual mean precipitation in the model produces a global mean RMS difference (0.67°C) which is almost identical to that of the standard monthly simulation.

[28] For easier interpretation of the results shown in spatial plots (Figure 3b), zonal averages of each statistical metric are also presented (Figure 5). For each case, comparisons are with respect to the standard all monthly simulation. The simulation forced with annual mean of vapor mixing ratio generally gives RMS SST differences higher than the simulation forced with annual mean shortwave radiation between 20°S – 30°N , especially in the eastern equatorial Atlantic and Pacific (Figure 3b). This result supports the fact that although shortwave radiation is the most dominant variable, affecting the SST seasonal cycle globally, vapor mixing ratio has greater influence in some specific latitude bands. Zonal averages of RMS values further demonstrate that precipitation does not have any noticeable effect on the SST seasonal cycle.

[29] Nondimensional skill score values generally decrease for simulations forced with annual mean shortwave radiation, wind speed, and vapor mixing ratio (Figure 3c). Shortwave radiation has little effect on the seasonal cycle of SST in the equatorial regions, but has a large effect at midlatitudes (Figure 6). This statement is consistent with the results presented by *Seager et al.* [1988], explaining that away from the equatorial regions, SST is primarily determined by a one-dimensional balance of heat storage in the mixed layer and surface heat flux, resulting in a simple

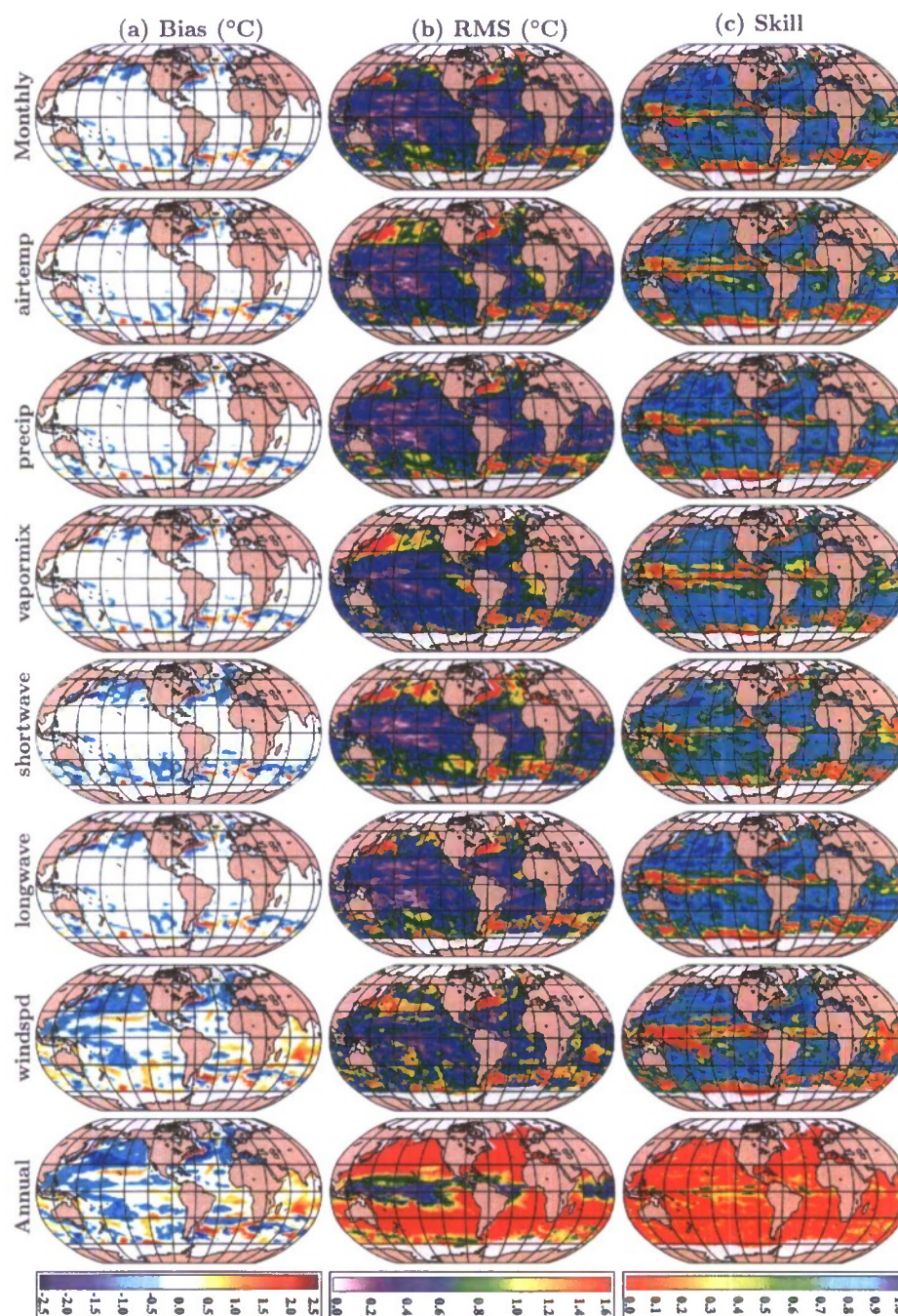


Figure 3. Spatial variations of statistical metrics comparing HYCOM with the NOAA SST climatology. The validation statistics are shown for each HYCOM simulation listed in Table 1. Regions where ice exists are in gray.

annual cycle of temperature. In addition, Kara *et al.* [2004] explained that some penetrating solar energy is normally trapped within and below the seasonal pycnocline in mid-latitudes where large seasonal variations in mixed layer depth occur. However, in equatorial regions the seasonal variation in solar energy is smaller than at midlatitudes.

[30] The reduction in the nondimensional skill values in comparison to the standard monthly simulation are not

systematic, i.e., there are variations over the global ocean (Figure 3c). Therefore we specifically examined zonal averages of three HYCOM simulations that resulted in relatively low skill values in comparison to the standard all monthly simulation but higher than the all annual simulation (Figure 7). The simulation using the annual mean vapor mixing ratio generally lowers the skill values more than wind speed at the latitudes north of 10°N when

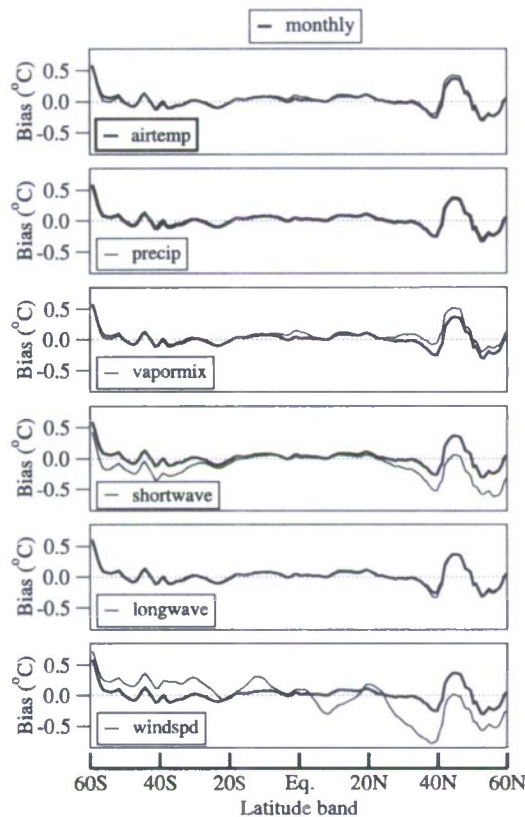


Figure 4. Comparisons of zonally averaged HYCOM SST bias with respect to the NOAA SST climatology. The HYCOM simulation that uses the monthly mean of all atmospheric forcing variables is compared with those that use all monthly means except for one annual mean forcing variable at a time. Average bias values over the basin are given in Table 2 for each simulation.

compared to the standard monthly simulation. However, the opposite is true just north of the equator. The SST skill from the annual mean wind speed simulation can be as low as that obtained from the simulation using the annual mean of all atmospheric forcing variables near 10°N. This makes wind speed the most important variable in driving the SST seasonal cycle in these regions.

Table 2. Global Averages of HYCOM SST Validation Statistics^a

| Simulation | Bias (°C) | RMS (°C) | Skill |
|------------|-----------|----------|-------|
| Monthly | 0.01 | 0.66 | 0.67 |
| Airtemp | 0.02 | 0.74 | 0.63 |
| Precip | 0.01 | 0.67 | 0.67 |
| Vapormix | 0.06 | 0.79 | 0.60 |
| Shortwave | -0.12 | 0.84 | 0.58 |
| Longwave | 0.01 | 0.70 | 0.65 |
| Windspd | -0.04 | 0.79 | 0.57 |
| Annual | -0.12 | 1.81 | -0.10 |

^aThe statistical values are with respect to NOAA SST climatology and are calculated using monthly means from HYCOM and NOAA SST over the seasonal cycle. The monthly NOAA SST fields are used for the model validation because they are designed mainly for large-scale climate studies and thus have resolution similar to the model.

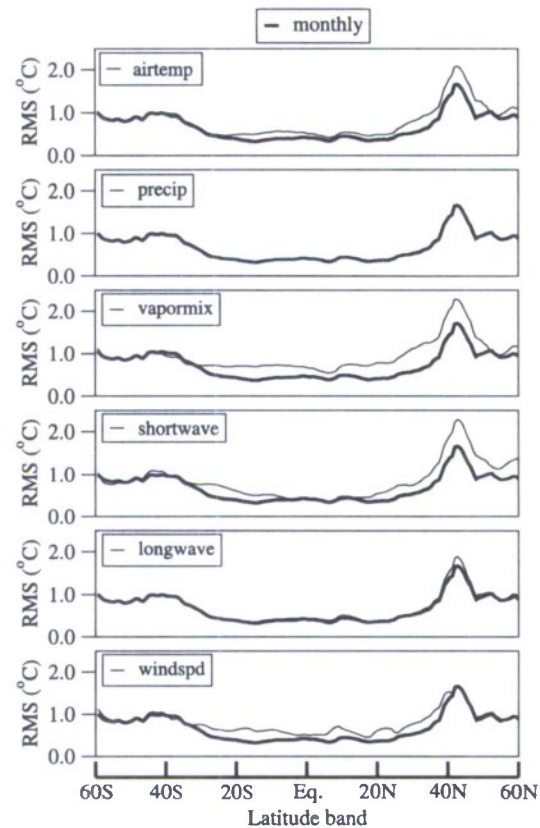


Figure 5. Same as Figure 4 but for RMS SST difference.

[31] When examining global averages of SST skill values (Table 2) with respect to the standard HYCOM simulation, which has a skill value of 0.67, one can notice a reduction of 16% (17%) in the SST skill for the simulation forced with annual mean shortwave radiation, skill = 0.58 (wind speed, skill = 0.57). Thus, unlike the RMS difference, wind speed along with the shortwave radiation are the most important variables that control the SST seasonal cycle in terms of SST skill over the global ocean. Similar to RMS SST difference, precipitation has still no effect on the SST seasonal cycle from the SST skill point of view, since a skill value of 0.67 for the HYCOM simulation that uses annual mean precipitation is the same as the skill value for the standard simulation.

[32] As a reference for results that can be expected in the best/worst case, Figure 8 shows zonal averages of all statistical metrics (bias, RMS and SS) calculated for HYCOM versus NOAA when the model is forced using the monthly versus the annual mean for each atmospheric variable (see Table 1). As expected, the simulation forced with the annual mean of each atmospheric variable gives unrealistic SSTs when compared to NOAA values. For example, there is almost no SST skill in the model at all latitudes for this particular simulation. In addition, RMS SST difference increases significantly (e.g., >300%) in comparison to the standard simulation at latitudes between 30°N–50°N (e.g., ≈1°C to ≈3°C).

[33] As explained above, differences in SST from model simulations arise from monthly versus annual mean atmo-

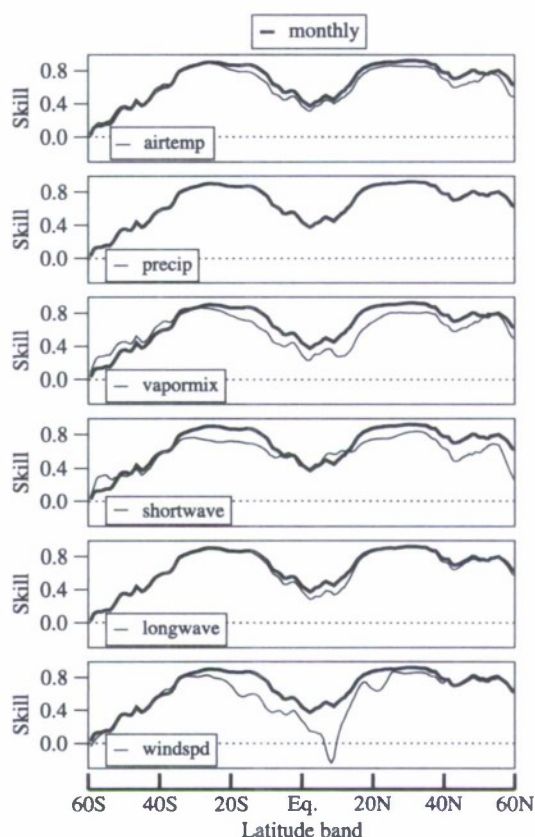


Figure 6. Same as Figure 4 but for SST skill score.

spheric forcing. To explain such differences we examine climatological monthly and annual mean time series of atmospheric forcing in combination with SST time series obtained from the simulations at a particular point (30°N, 75°W) located near the Gulf Stream region (Figure 9). This location is chosen just for illustrative purposes.

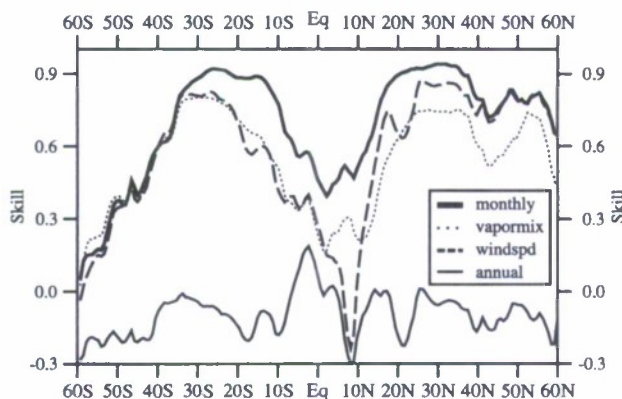


Figure 7. Zonally averaged SST skill values for HYCOM versus the NOAA climatology. Atmospheric forcing variables used in the model simulation are composed of all monthly means, all monthly means but annual mean vapor mixing ratio, all monthly means but annual mean wind speed, and all annual means.

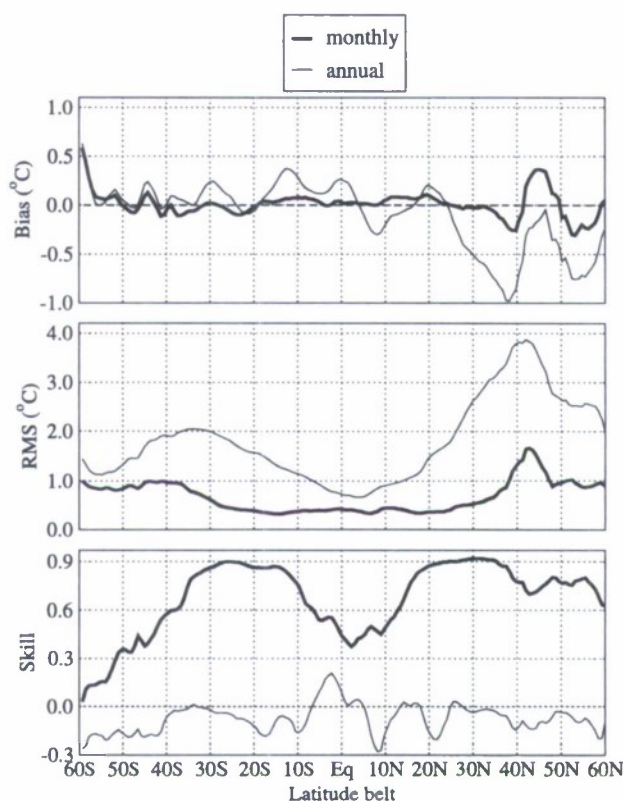


Figure 8. Zonal averages of SST bias (mean error), RMS SST difference, and SST skill score for HYCOM versus the NOAA climatology. Results from the HYCOM simulations using monthly and annual mean for each atmospheric forcing variable are shown.

[34] In Figure 9, we compare SST time series with the standard simulation. All atmospheric variables have clear seasonal signals at this particular location. Obviously, the use of an annual mean of any variable results in an SST error that is usually related to the difference in forcing (annual-monthly). For example, the simulation forced with annual mean vapor mixing ratio overestimates SST in comparison to the standard monthly simulation from January through May, and annual mean of vapor mixing ratio is less than the actual monthly mean mixing ratio during this time period. A similar situation also holds for shortwave radiation. While longwave radiation also has a clear seasonal variation, its range ($\approx -73 \text{ W m}^{-2}$ to $\approx -55 \text{ W m}^{-2}$) is small, resulting in almost no change in SST. Because of the seasonal cycle for each variable, the simulation that uses annual mean of all atmospheric variables yields extremely unrealistic SSTs (Figure 10).

5. Which Variable Controls SST Most?

[35] Discussions presented in section 4 explain that the most important atmospheric forcing variable in driving the climatological mean SST seasonal cycle varies by region. In this section, our goal is to (1) present a quantitative analysis for determining the importance order (from the most to the least) of atmospheric forcing variables in controlling the SST seasonal cycle (section 5.1), and (2) investigate

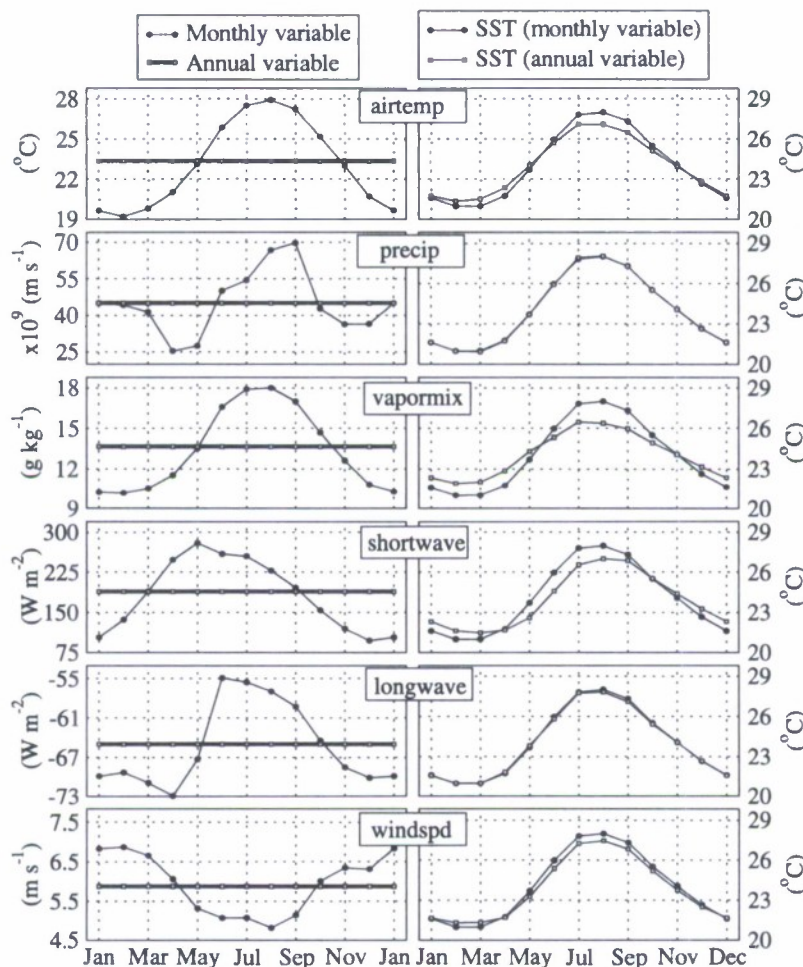


Figure 9. (left) Climatological monthly and long-term (annual) mean of atmospheric forcing variables at 30°N, 75°W and (right) monthly mean SST time series when HYCOM is forced using the monthly mean of all atmospheric forcing variables (monthly) and using the twin of this simulation (i.e., all monthly forcing) but the annual mean of one variable at a time. For example, airtemp stands for the model simulation that is forced with annual mean air temperature but monthly otherwise (i.e., monthly means of precip, vapormix, shortwave, longwave, and windspd).

whether or not there are factors (c.g., oceanic upwelling) other than atmospheric forcing that affects the SST seasonal cycle significantly (section 5.2).

5.1. Importance Order for Atmospheric Variables

[36] Because the most important variable controlling the SST for a given statistical metric (e.g., RMS) may not be the same one for another statistical metric (c.g., skill) as demonstrated above, we determine the importance order of the atmospheric variables for bias, RMS and skill, separately.

[37] The procedure for finding an importance order (from the most to the least) of atmospheric variables in driving the SST cycle at each ocean model grid over the global ocean is as follows:

[38] 1. Bias, RMS and skill values for HYCOM versus NOAA SST values are obtained for each model simulation, namely airtemp, precip, vapormix, shortwave, longwave and windspd (Table 1).

[39] 2. The statistical values for each simulation are ordered from the largest to the smallest.

[40] 3. For bias and RMS SST difference, the most important variable (#1) is the one whose annual mean used in the model simulation gives the largest value. The simulation giving the second (third, fourth, fifth and sixth) largest value is chosen as the second (third, fourth, fifth and least) most important variable.

[41] 4. Similarly for SST skill, the most important variable (#1) is the one whose annual mean used in the model simulation gives the smallest value. The simulation giving the second (third, fourth, fifth and sixth) smallest skill value is chosen as the second (third, fourth, fifth and least) most important variable.

[42] Note that for the purpose of determining the importance order of each variable in terms of bias, the absolute value is used because we are not interested in the sign of the bias. While it is not very common, if values for a given statistical metric are exactly the same for two or more

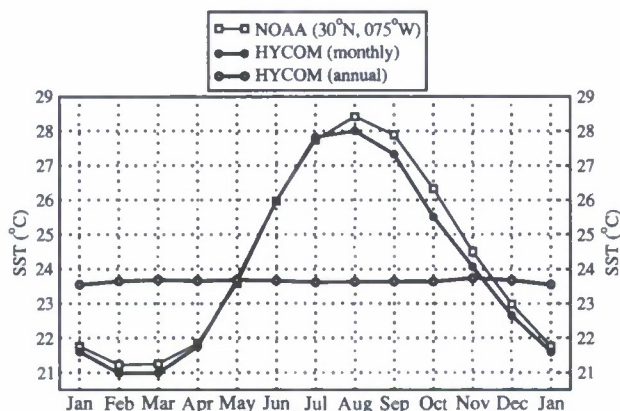


Figure 10. Comparisons of climatological monthly mean SST time series at 30°N, 75°W. Comparisons are made between the NOAA SST climatology and SST obtained from two climatologically forced HYCOM simulations: One (i.e., monthly) uses the monthly mean of each atmospheric variable, and the other (annual) uses annual mean of each atmospheric forcing variable. Atmospheric forcing variables described in the text are airtemp, precip, vapormix, shortwave, longwave, and windspd.

simulations, the first in the variable order (above) is picked first. The importance order for each variable is then determined.

[43] As examples to illustrate the procedure for determining the importance order of each atmospheric variable on the SST seasonal cycle, Table 3 provides a statistical evaluation of the HYCOM SST in comparison to NOAA SST at five locations over the global ocean. The first thing to note from the table is that the monthly (annual) simulation nearly always results in the best (worst) SST simula-

tion, implying robustness of the model. Other simulations that use the annual mean of any given variable give SST statistics between the monthly and annual cases.

[44] Wind speed (precipitation) is the most (least) important atmospheric variable in determining the annual mean SST at (30°N, 75°W) in the Gulf Stream region because that simulation has the highest (lowest) bias of -0.49°C (-0.27°C) in comparison to the other simulations (Table 3). Vapor mixing ratio becomes the most important variable in controlling the RMS SST difference at the same location, giving the largest value of 1.10°C . Finally, in terms of SST skill the simulation forced with annual mean vapor mixing ratio has the lowest skill value of 0.80 among other simulations, making it again the most important variable.

[45] The same variable ordering procedure performed at the individual locations (Table 3) was applied at all 0.72° HYCOM model grid points, so that maps of importance order for each variable that regulates the SST seasonal cycle could be obtained over the global ocean. Figure 11 clearly demonstrates spatial variability in the most and least important atmospheric variables that drive the SST seasonal cycle. The most and least important variables are generally the same for the RMS SST difference and SST skill.

[46] Wind speed is certainly the most important variable in maintaining the climatological mean SST bias over the global ocean (Figure 11a). However, net solar radiation, which includes both shortwave and longwave radiation at the sea surface, takes on the greatest importance in terms of RMS and skill. A common feature of the mean bias, RMS, and skill maps, illustrating the most important variables, is that vapor mixing ratio is generally the only one that has a substantial effect on the SST seasonal cycle in most of the tropical Pacific, especially the eastern and central equatorial Pacific.

[47] Results given in Figure 11a are generally consistent with those reported in earlier studies. For example, evaporative

Table 3. HYCOM SST Evaluation and Importance Order for Atmospheric Variables^a

| Location | Monthly | Airtemp | Precip | Vapormix | Shortwave | Longwave | Windspd | Annual |
|--|---------|--------------|-------------|--------------|--------------|--------------|--------------|--------|
| Bias ($^{\circ}\text{C}$) Values for HYCOM Versus NOAA SST Climatology | | | | | | | | |
| (00°N, 145°W) | 0.10 | 0.16 fourth | 0.18 third | 0.25 most | 0.18 second | 0.15 fifth | -0.11 least | 0.30 |
| (10°S, 110°W) | 0.19 | 0.19 fourth | 0.19 third | 0.20 second | 0.19 fifth | 0.19 least | 0.22 most | 0.24 |
| (30°N, 075°W) | -0.26 | -0.36 third | -0.27 least | -0.31 fourth | -0.48 second | -0.30 fifth | -0.49 most | -0.80 |
| (20°S, 070°E) | 0.08 | 0.08 third | 0.08 fourth | 0.11 second | -0.08 least | 0.08 fifth | 1.80 most | 2.10 |
| (35°N, 145°E) | 0.20 | 0.27 third | 0.24 fourth | 0.52 most | 0.17 least | 0.21 fifth | -0.29 second | -0.13 |
| (45°S, 180°E) | -0.32 | -0.32 fourth | -0.32 third | -0.28 least | -0.50 most | -0.37 second | -0.28 fifth | -0.60 |
| RMS ($^{\circ}\text{C}$) Values for HYCOM Versus NOAA SST Climatology | | | | | | | | |
| (00°N, 145°W) | 0.30 | 0.37 fifth | 0.33 least | 0.40 most | 0.39 third | 0.38 fourth | 0.39 second | 0.44 |
| (10°S, 110°W) | 0.32 | 0.48 second | 0.32 fifth | 0.55 most | 0.46 third | 0.32 least | 0.35 fourth | 0.93 |
| (30°N, 075°W) | 0.37 | 0.75 third | 0.38 least | 1.10 most | 0.85 second | 0.44 fifth | 0.64 fourth | 2.70 |
| (20°S, 070°E) | 0.26 | 0.45 fourth | 0.26 least | 0.70 second | 0.58 third | 0.27 fifth | 1.90 most | 2.70 |
| (35°N, 145°E) | 0.47 | 1.20 second | 0.50 least | 1.70 most | 0.97 third | 0.68 fifth | 0.75 fourth | 3.40 |
| (45°S, 180°E) | 0.39 | 0.56 third | 0.40 fifth | 0.59 second | 1.50 most | 0.43 fourth | 0.34 least | 2.20 |
| Skill Values for HYCOM Versus NOAA SST Climatology | | | | | | | | |
| (00°N, 145°W) | 0.48 | 0.28 fifth | 0.43 least | 0.23 fourth | 0.20 second | 0.22 third | 0.14 most | 0.08 |
| (10°S, 110°W) | 0.83 | 0.60 second | 0.82 fourth | 0.53 most | 0.64 third | 0.83 least | 0.83 fifth | 0.04 |
| (30°N, 075°W) | 0.97 | 0.90 third | 0.97 least | 0.80 most | 0.87 second | 0.96 fifth | 0.93 fourth | -0.08 |
| (20°S, 070°E) | 0.95 | 0.85 fourth | 0.95 least | 0.73 second | 0.79 third | 0.94 fifth | -0.06 most | -0.75 |
| (35°N, 145°E) | 0.97 | 0.86 second | 0.97 least | 0.72 most | 0.89 third | 0.95 fifth | 0.94 fourth | -0.04 |
| (45°S, 180°E) | 0.96 | 0.91 third | 0.96 fifth | 0.91 second | 0.47 most | 0.95 fourth | 0.97 least | -0.04 |

^aFor each statistic, the importance order of each variable at each location is listed as most, second, third, ..., least. SST statistics (i.e., bias, RMS, and skill) are calculated for HYCOM versus NOAA SSTs over the seasonal cycle (i.e., using 12 monthly means). The atmospheric variables are ranked in order of importance based on the statistical values.

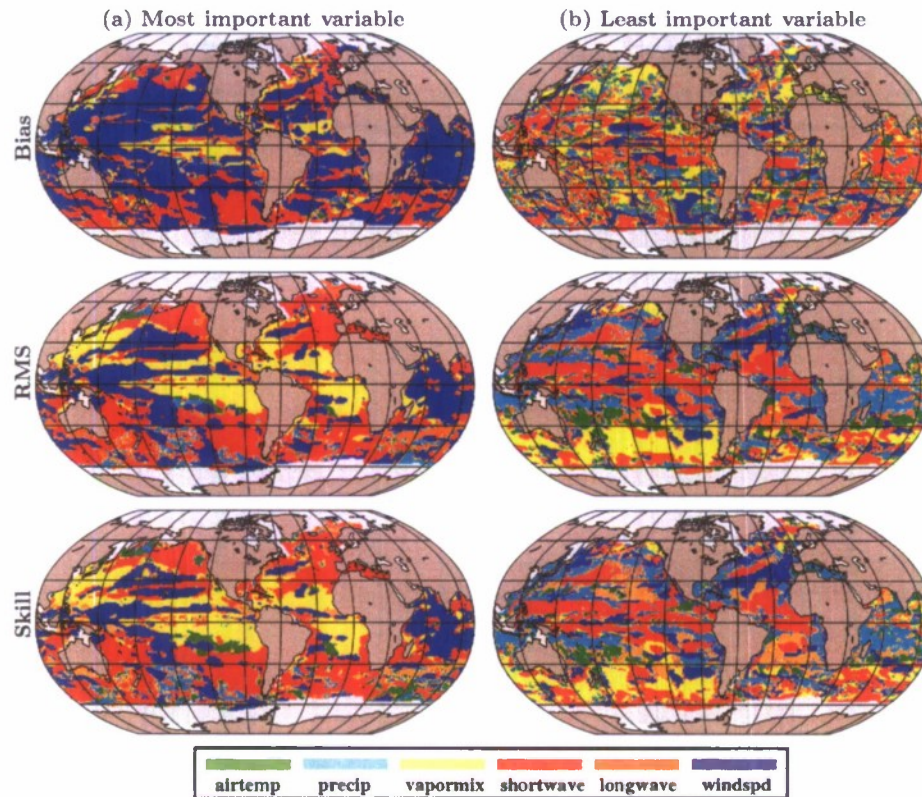


Figure 11. Regions showing which atmospheric variable controls the SST seasonal cycle over the global ocean. The (a) most and the (b) least important variables that are effective in driving the monthly mean SST cycle are given in terms of SST bias, RMS SST difference, and SST skill score. For example, shortwave radiation at the sea surface is generally the most important atmospheric forcing variable in obtaining an accurate SST seasonal cycle in the North Atlantic and North Pacific Oceans when evaluating results in terms of RMS and skill.

flux variability plays a significant role in modifying SST, especially in the warm pool, and SST in the Indian Ocean is typically less sensitive to surface thermal variables (i.e., shortwave and longwave radiation, air temperature, etc.) than the wind forcing [Fasullo and Webster, 1999]. As to the least important variables (Figure 11b), vapor mixing ratio at the high southern latitudes and wind speed over the most of the North Atlantic have little effect on the SST seasonal cycle. This is true for both RMS SST difference and SST skill.

[48] A final assessment is performed using the information displayed in Figure 11. We calculate the percentage area of the global ocean where an atmospheric variable is important (Table 4). Also included are second, third, fourth and fifth most important atmospheric variables. On the basis of these percentages for the nondimensional SST skill score, shortwave radiation can be considered as the main parameter in driving the SST seasonal cycle since it is ranked as the most important variable for about 34.3% of the global ocean. The wind speed is ranked first over the second largest area.

[49] The variables ranked second and third over the largest area are vapor mixing ratio and air temperature, respectively. Precipitation (23.6%) and shortwave radiation

Table 4. Importance Order of Variables as a Percentage of Global Ocean Coverage^a

| Variable | Most | Second | Third | Fourth | Fifth | Least |
|---|------|--------|-------|--------|-------|-------|
| Percentage of Region for SST Bias Importance | | | | | | |
| Airtemp | 1.1 | 11.9 | 24.7 | 28.5 | 24.3 | 9.5 |
| Precip | 2.1 | 10.1 | 20.9 | 24.7 | 24.9 | 17.3 |
| Vapormix | 9.9 | 19.6 | 17.7 | 15.4 | 18.0 | 19.4 |
| Shortwave | 19.6 | 26.4 | 9.8 | 8.9 | 10.5 | 24.8 |
| Longwave | 6.8 | 23.1 | 22.9 | 18.6 | 17.5 | 11.1 |
| Windspd | 60.5 | 8.9 | 4.0 | 3.9 | 4.8 | 17.9 |
| Percentage of Region for RMS SST Importance | | | | | | |
| Airtemp | 1.6 | 16.4 | 26.1 | 29.9 | 17.1 | 8.9 |
| Precip | 5.1 | 11.8 | 13.2 | 16.6 | 28.5 | 24.8 |
| Vapormix | 22.0 | 23.4 | 18.5 | 7.7 | 12.7 | 15.7 |
| Shortwave | 29.8 | 19.9 | 11.1 | 9.0 | 7.7 | 22.5 |
| Longwave | 8.0 | 15.1 | 16.8 | 23.0 | 24.7 | 12.4 |
| Windspd | 33.5 | 13.4 | 14.3 | 13.8 | 9.3 | 15.7 |
| Percentage of Region for SST Skill Importance | | | | | | |
| Airtemp | 5.3 | 20.9 | 30.0 | 24.7 | 12.6 | 6.5 |
| Precip | 4.7 | 10.1 | 12.4 | 18.9 | 30.3 | 23.6 |
| Vapormix | 21.7 | 25.4 | 19.2 | 8.5 | 12.3 | 12.9 |
| Shortwave | 34.3 | 16.9 | 9.1 | 7.4 | 6.8 | 25.5 |
| Longwave | 6.8 | 13.1 | 16.4 | 25.2 | 25.0 | 13.5 |
| Windspd | 27.2 | 13.6 | 12.9 | 15.3 | 13.0 | 18.0 |

^aThe importance of the atmospheric forcing variable is ordered (from the most important to the least important) for the given SST statistics.

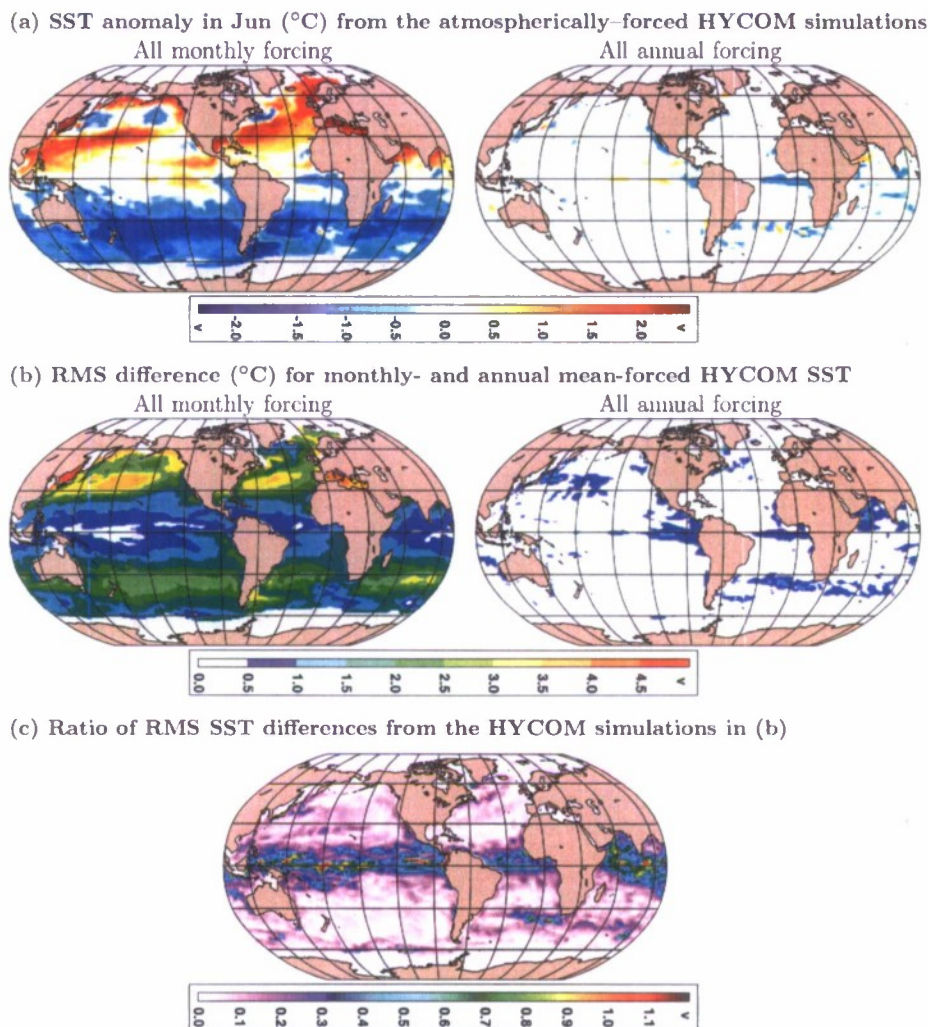


Figure 12. A comparison of monthly mean SST statistics obtained when HYCOM is forced with monthly means or annual means of all the atmospheric variables.

(25.5%) are ranked as the least important variables over the largest area (Table 4). The latter might be surprising since shortwave radiation was also found to be the most important variable over much of the global ocean (see Figure 11). This is due to regional differences (e.g., shortwave is the least important variable near the equator).

5.2. How Important is the Atmospheric Signal?

[50] The preceding analyses are based on the assumption that atmospheric thermal forcing variables are the main contributors in driving the SST seasonal cycle. This raises another question. Are there sources other than atmospheric variables that are important in controlling the SST seasonal cycle, and if yes, where in the global ocean? These questions can be addressed by determining the ratio of SST variability over the annual cycle from the constant forcing simulation with respect to the standard monthly forced simulation. Here, the constant forcing simulation is the one performed using the annual mean of all the atmospheric variables, and is generally expected to yield nearly constant SST over the seasonal cycle in most of global ocean.

[51] We first calculate the long-term climatological annual mean of SST fields over the seasonal cycle. Anomalies are then obtained by subtracting the long-term mean SST from that in each month over the global ocean. For example, SST anomalies are almost zero for the constant forcing case, as illustrated for June using the simulation forced with the annual mean of each atmospheric variable (Figure 12a). There are still significant SST anomalies in some regions. The all annual mean forcing simulation simply indicates that a constant heat flux derived from air temperature, vapor mixing ratio, wind speed, and net shortwave and longwave radiation was used in driving the simulation. The nonzero anomalies clearly reveal the existence of other significant sources of SST anomalies in some regions.

[52] While the simulation uses annual mean thermal forcing, seasonal variability due to wind stress forcing in the momentum equation is retained. Thus dynamical influences on SST are retained, e.g., wind-driven upwelling, especially equatorial upwelling in the eastern and central Atlantic and Pacific and wind-driven upwelling in the Arabian Sea (the northwestern Indian Ocean). However,

the model resolution is too coarse to be effective in simulating some dynamical influences on SST, such as coastal upwelling, advection by strong currents like the Gulf Stream and Kuroshio, mesoscale eddies, and strong ocean fronts, including the meanders of sharp fronts associated with ocean currents. The eddies and frontal meanders are largely the consequence of flow instabilities that the model resolves only to a very limited extent. The model does weakly depict a few of the poorly resolved phenomena, as seen in Figure 12a, e.g., in the Kuroshio and Gulf Stream regions, off the west coast of North America, and between the southern tip of Africa and South America.

[53] To further demonstrate the existence of dynamical impacts on the monthly mean SST, the RMS difference between monthly and annual mean HYCOM SST is calculated for both simulations, separately over the seasonal cycle (Figure 12b). These are simply RMS fields of the monthly SST anomalies. RMS difference with respect to the annual mean SST anomaly for the simulation forced with the annual mean of all atmospheric variables is typically very small ($<0.5^{\circ}\text{C}$) over the majority of the global ocean. It is much smaller than the standard monthly forced simulation.

[54] Using the RMS SST difference fields, a ratio of RMS anomalies between the two simulations is formed (Figure 12c). This is exactly the fraction of total variability from constant forcing, i.e., from sources other than near-surface atmospheric variability due to air temperature, precipitation, vapor mixing ratio, shortwave and longwave radiation and wind speed. Ratio values close to 1 are found in tropical regions, including the northwestern Indian Ocean and western equatorial Pacific warm pool. Thus the constant (all annual) forcing case represents a significant fraction of the total variability almost entirely in these regions, indicating that the thermal forcing variables dominate the seasonal cycle of SST everywhere else. In some regions, like the western equatorial Pacific warm pool, the ratio is large where the seasonal variability driven by both thermal forcing and dynamical effects is small.

6. Conclusions

[55] In this study we have ranked the impact of six atmospheric thermal forcing variables in driving the seasonal cycle of climatological SST over the global ocean. These variables are near-surface air temperature, precipitation, near-surface air mixing ratio, shortwave radiation, longwave radiation and near-surface wind speed. All analyses are performed using simulations by an OGCM with 0.72° resolution.

[56] One of the major points of this study is to reveal which atmospheric forcing variable has the greatest influence in driving the seasonal cycle of SST, so that an ocean modeler or coupled atmosphere-ocean modeler can pay specific attention to the accuracy of that specific atmospheric forcing variable before using it in a simulation. The importance order of atmospheric variables in driving the seasonal cycle of SST would also be valuable for various types of air-sea interaction studies over the global ocean, including interpretation and improvement of the results.

[57] There are five main conclusions stemming from results presented in this paper.

[58] 1. When considering the contribution of the seasonal cycle to the climatological annual mean of SST, the near-surface wind speed has the greatest impact and solar radiation (shortwave and longwave radiation) at the sea surface has the second largest impact.

[59] 2. On the basis of the nondimensional skill score, the SST seasonal cycle is primarily driven by shortwave radiation, wind speed, and vapor mixing ratio (over 33.5%, 27.2% and 21.7% of the global ocean, respectively). Thus there is not a single most important variable.

[60] 3. Vapor mixing ratio is the most important variable in tropical regions, especially in the eastern and central equatorial Atlantic and Pacific. Therefore latent heat flux is crucial in driving SST in these regions.

[61] 4. Precipitation at the sea surface is generally the least important variable.

[62] 5. Factors other than the near-surface atmospheric variables are most significant in tropical regions, at least in these 0.72° simulations.

[63] A simulation using the annual mean of all thermal atmospheric forcing variables (i.e., constant thermal forcing in time) represents a significant fraction of the total variability in tropical regions and in the northwestern Indian Ocean (i.e., the Arabian Sea). In these regions, this result demonstrates the relative importance of sources other than the near-surface atmospheric variables in regulating the SST seasonal cycle.

Appendix A: HYCOM Description

[64] Twenty-six hybrid layers are used in the 0.72° global HYCOM simulations performed for this study. The layers are in pressure coordinates (approximately z levels) in the surface mixed layer and unstratified water, terrain following in shallow water and isopycnal in the stratified interior. The minimum thickness of the upper layer (i.e., layer 1) is 3 m, and this increases $1.125\times$ per layer up to a maximum at 12 m. The simulations use realistic bottom topography constructed from the NRL 2 minute resolution bathymetric data set. The model land-sea boundary is at the 50 m isobath.

[65] HYCOM uses a penetrating solar radiation scheme that accounts for the effects of spatial and temporal variations in water turbidity [Kara et al., 2005a]. This scheme is designed to improve the simulation of upper ocean quantities, especially SST. The net longwave flux is the sum of downward longwave (from the atmosphere) and upward blackbody radiation. The blackbody radiation from ERA-40 is corrected to allow for the difference between ERA-40 SST and HYCOM SST [Kara et al., 2005b]. Latent and sensible heat fluxes at the air-sea interface are calculated using efficient and accurate bulk parameterizations [Kara et al., 2005c]. Thus the surface heat fluxes depend on the atmospheric variables used in this study and a model SST. HYCOM treats rivers as a runoff addition to the surface precipitation field. All simulations use the K-Profile Parameterization (KPP) level 1 turbulence closure [Large et al., 1997]. Other available mixed layer models in HYCOM typically give similar SSTs [Kara et al., 2008].

[66] As explained in the text, some corrections are applied to the atmospheric forcing from ERA-40. A climatological annual (long-term) mean correction rather than a climatological monthly mean correction is preferred because

(1) sufficient data and a long-enough time series are not available for a monthly correction, and (2) a monthly correction to a monthly gridded product removes all effect of the operational weather product.

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